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SEA SURFACE WIND SPEED FROM SPACE

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SEA SURFACE WIND SPEED FROM SPACE

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ABSTRACT

The availability of sea surface slope variance and reflectance as a function of wind speed at the sea surface makes possible the measurement of that wind speed from space. This paper treats a simple case, i.e., flat-earth, using vertical viewing and solar flux. Generalization to a spherical earth, oblique viewing and radar as well as optical wavelengths is possible.

FOOTNOTE TO ABSTRACT

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Some years ago, Cox and Munk [1954] showed through recourse to photographs of sun's glitter that the variance of sea surface slopes was a linear function of wind speed over the sea surface. In fact, they developed all the methodology for measuring sea surface wind speed from aloft lacking only sea surface radiance over a range of wind speeds to effect the method. Recently Martin [1966] has determined such a relationship.

Simply put, if an optical or radar sensing system views a sea surface glittering spot of electromagnetic waves then, given the local intensity of glitter within the spot as a function of spot off-center angle, one may deduce wind speed. Furthermore, as up-wind and cross-wind clean surface slope variances differ by a factor of as much as 1.5 one might, in principle, deduce wind direction also if wind speeds are large enough.

Rather than immediately complicate matters by involving spherical geometry and radiant source and sensing system in general positions, it is better to describe the idea by using flat earth and a plane vertical to it.

Cox and Munk showed that for both clean sea surface and slick sea surface, for both cross-wind and up-wind directions, slope variance $\sigma_{z'}^2$, may be represented as

$$\sigma_{z'}^2 = a + bv \tag{1}$$

where v is wind speed measured 41 feet above sea level and a and b are constants depending upon sea surface cleanliness and wind direction. The appropriate values are given in Table 1 for v in m/sec.

TABLE 1. Coefficients for Sea Surface Slope Variance (cf. Eq. 1, Cox & Munk [1954])

Surface Condition	Constant, a		Wind Speed Coefficient, b	
	Up-wind	Cross-wind	Up-wind	Cross-wind
Clean Surface	0.000	0.003	0.00316	0.00192
Slick Surface	0.005	0.003	0.00078	0.00084

The other necessary basis for estimating sea surface wind speed from aloft is the surface reflection strength as a function of wind speed and geometry of interest. Without distinguishing between clean or slick surfaces, Martin [1966, 1968A] gives reflection strength J based on acoustic, radar, laser, and water surface slope spectra data as follows:

$$J = J_o(v) \exp\left[-\tfrac{1}{2}\left(\frac{\tan\theta}{\sigma_z^2{}'}\right)^2\right] \tag{2}$$

where $J_o(v)$ is the reflection strength of the sea surface along rays from specular points on the surface with local slope $\theta = 0$. As a function of wind speed, $J_o(v)$ expressed in decibels, i.e., $N_o(v) \equiv 10 \log J_o(v)$, is given the form of an error integral, i.e., (Martin [1968A])

$$N_o(v) = (A/\sqrt{2\pi}\ \sigma)\int_{-\infty}^{x} \exp\left\{-\tfrac{1}{2}\left[(x'-\mu)/\sigma\right]^2\right\} dx' \tag{3}$$

where $x = \ln v$, $A = -10$, $\mu = \ln$ (4.9 m/sec) and $\sigma = \ln$ (1.95 m/sec).

Now with the foregoing as basis, assume that the geometry of Fig. 1 is of interest. That is, the sun's rays are illuminating the sea surface at normal incidence and the sensing system is viewing normal to the sea surface also. In Eq. 2, it is apparent--from Fig. 1--that θ, the local slope required for specular reflection, is replaced by φ the off-axis viewing angle of the sensing system. Hence, with Eqs. 1, 2, and 3, one may compute reflection strength $N(v, \varphi)$ as shown in Fig. 2.

Figure 2 is calculated as if there were no attenuation between the source surface and sensing system, which need not be the case. However, in case transmission of the atmosphere is unity, then a measurement of glitter spot center intensity is a direct measure of sea surface wind velocity. In addition, under such a circumstance the measurement of N_o (v, φ), where φ is an arbitrary but fixed value, determines v redundantly, as implied by Fig. 2.

More likely, however, transmission of the atmosphere will be less than unity and unknown and glitter spot center relative intensity as well as N (v, φ) will be required to fix v, the sea surface wind speed. To this end suppose, for example, that the sensing system has a "gate" of sensitivity with a 40-db dynamic range, and that by means of attenuators or filters, this dynamic range is "tunable." Thus to determine v_1 the gate would be tuned so as to cause the glitter spot maximum intensity to be at the point of saturation and the spot size threshold level would then determine wind speed. For the threshold shown in Fig. 2, i.e., 40 db, it happens that v varies about as φ^2.

It seems clear that if one were to trace out the glitter spot in two dimensions on the surface that an oblong spot would develop due to the variance differences indicated in Table 1. For the same 40-db gate postulated above, Fig. 3 shows glitter spot size for various wind speeds. At low wind speeds, the major axis of the ellipse is in the cross-wind direction--or so Table 1 and Eq. 1 indicate--and with increasing wind speed the major axis turns to the windward direction. The properties of conics indicate that the pattern is circular at about 2.5 m/sec and that the asymptotic eccentricity of the elliptical glitter spot at large wind speeds is about 5/8. Because the glitter spot angular extent φ varies as $v^{\frac{1}{2}}$ and as the area of the glitter spot varies as φ^2, it appears that in addition to measuring angular extent to estimate wind speed, a raster scan (area integration) of the glitter spot could give a measurement of wind speed also.

A comment on the 40-db threshold of the example is warranted. The technique being used depends upon reflection from "facets" of sea surface rather than upon scattering due to resonance between incident

radiation and Fourier components of the sea surface elevation. Thus, reflection strength must be large enough so that it is not confused with scattering strength. There is some evidence [Martin, 1968A] that for wavenumbers less than about 50/cm (wavelength $\cong$ 1 to 2 mm) that an upper bound on unattenuated scattering strength is -26 db even at the greatest wind speeds. At wavenumbers greater than 50/cm, sea surface elevation spectral density drops off very rapidly [Martin, 1968B] with increasing wavenumber so that a 40-db dynamic range is not unreasonable for optical (IR-UV) wavelengths.

Thus it appears that the combined variation of sea surface reflectance and slope variance is suitable for measuring sea surface wind speed. These wind speed measurements could be made by passive or active, optical, electro-optical or radar systems, and might yield in addition wind direction--with an uncertainty of 180 deg. at large enough wind speed. The 180 deg. uncertainty might be removed by recourse to atmospheric circulation principles or to other data.

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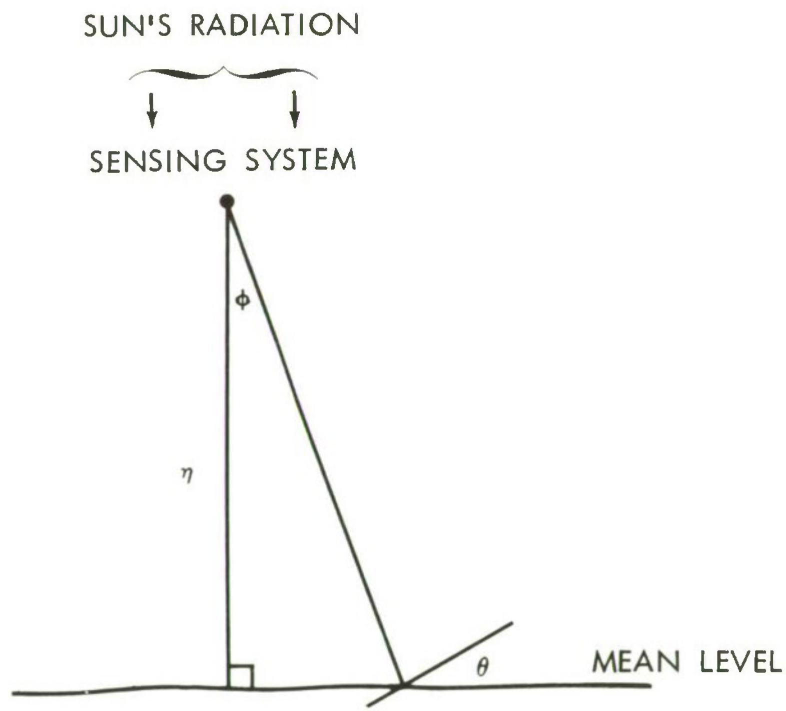
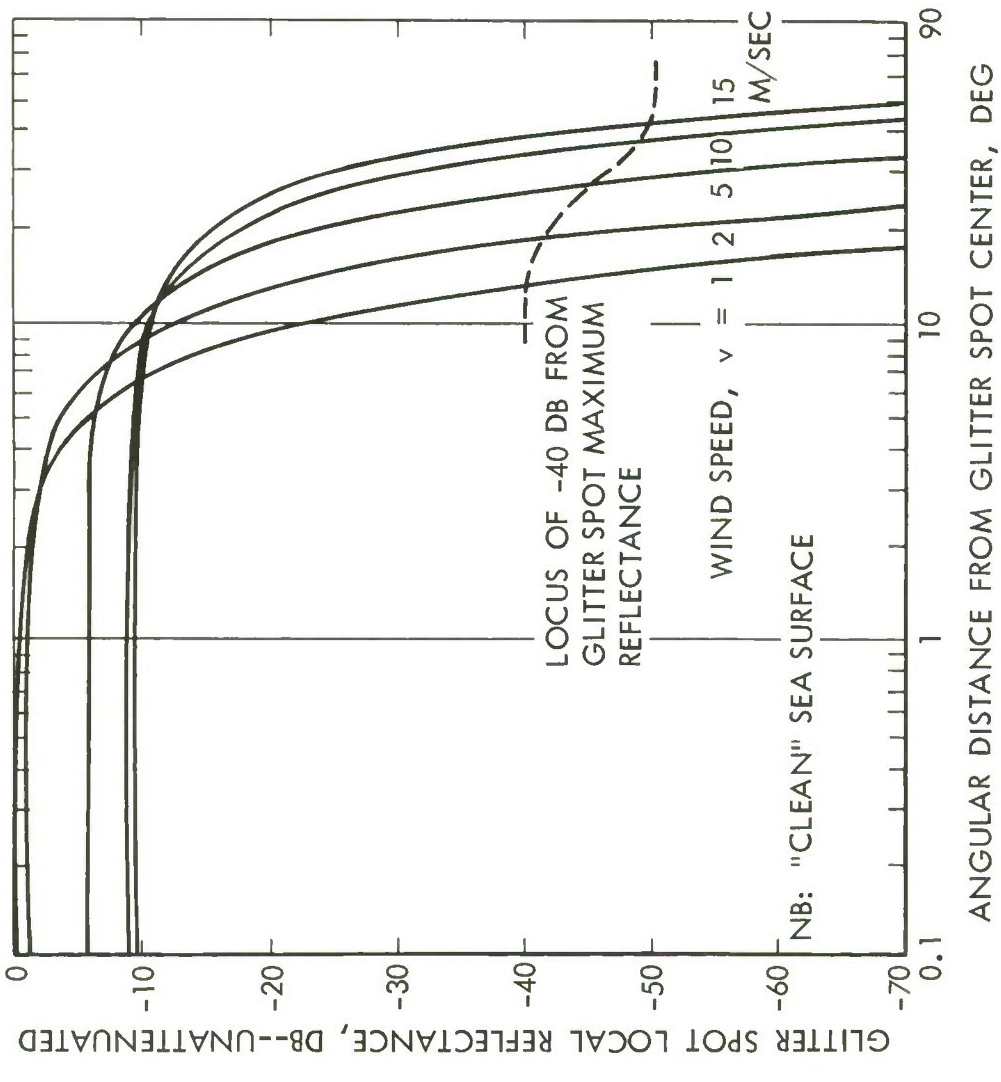
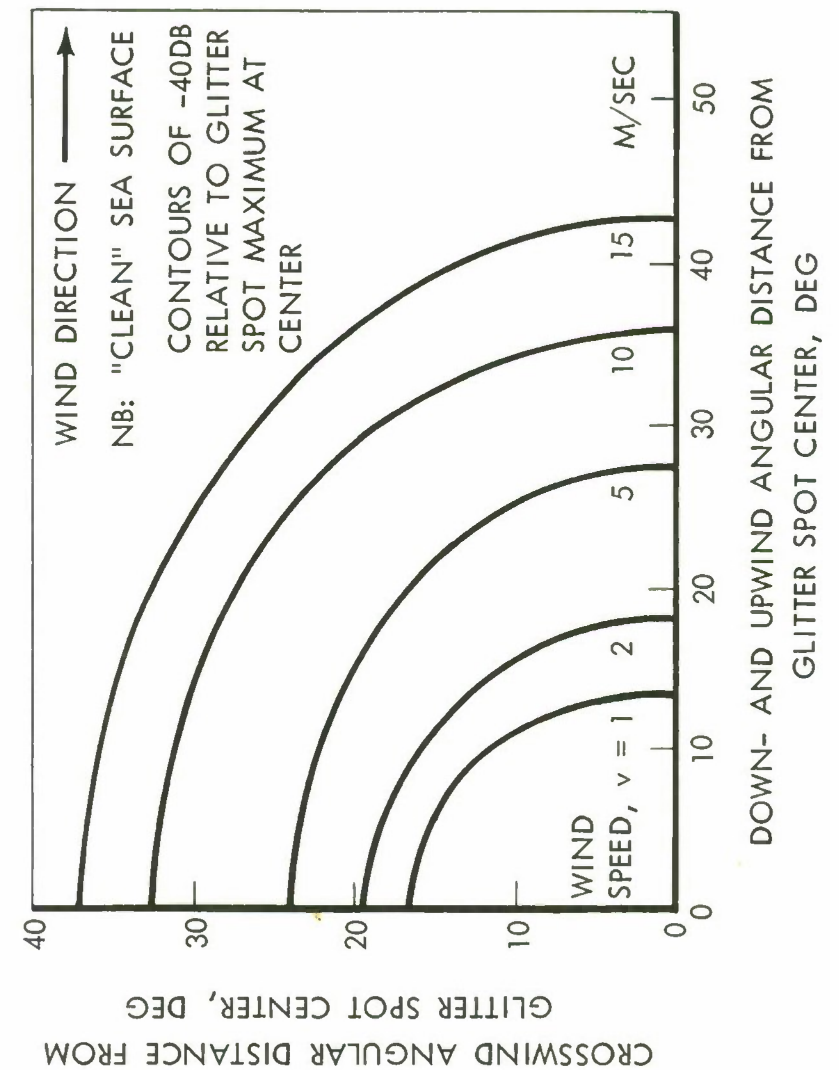

SUN'S RADIATION
SENSING SYSTEM
φ
η
θ
MEAN LEVEL



GLITTER SPOT LOCAL REFLECTANCE, DB--UNATTENUATED
0
-10
-20
-30
-40
-50
-60
-70
0.1
1
10
90
ANGULAR DISTANCE FROM GLITTER SPOT CENTER, DEG
LOCUS OF -40 DB FROM
GLITTER SPOT MAXIMUM
REFLECTANCE
WIND SPEED, v = 1 2 5 10 15
M/SEC
NB: "CLEAN" SEA SURFACE


WIND DIRECTION
NB: "CLEAN" SEA SURFACE
CONTOURS OF -40DB RELATIVE TO GLITTER SPOT MAXIMUM AT CENTER
WIND SPEED, v = 1
2
5
10
15
M/SEC
0
10
20
30
40
50
DOWN- AND UPWIND ANGULAR DISTANCE FROM GLITTER SPOT CENTER, DEG
0
10
20
30
40
CROSSWIND ANGULAR DISTANCE FROM GLITTER SPOT CENTER, DEG

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